Rapid Composting Using a Novel Agricultural Waste Shredder

*[1]Rasheed A. Busari, [2]Kehinde P. Alabi, [3]Raheef K. Adebayo, and [4]Juwon O. Dada
[1,2,3,4]Department of Food and Agricultural Engineering, Kwara State University, Malete, Kwara State, Nigeria
rasheed.busari@kwasu.edu.ng, kehinde.alabi@kwasu.edu.ng, kehinde.adebayo@kwasu.edu.ng

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ORIGINAL RESEARCH

Abstract— Agricultural waste causes social and environmental pollution, affecting global health. Converting agricultural waste to organic manure reduces the problems of pollution. Existing machine used in conversion has low efficiency in terms of throughput capacity and size reduction, leading to slow composting. This study focuses on the evaluation of a specially developed waste shredder for fast composting (maize straw). The machine was designed to handle substantial volumes of agricultural waste, operated at different speeds (i.e. 300, 600, 900, 1200 and 1500 rpm) and time (i.e. 0.5, 10, 1.5, 2.0 and 2.5 hr). The components of the machine included shredding drum equipped with three sets of blades, a feeding tray, sieve, engine seat and an outlet. Performance evaluation carried on the machine includes shredding efficiency and throughput capacity. A standardized Response surface methodology (RSM) was employed to maximize efficiency varying the operational speeds and shredding time. Results showed achieved maximum shredding efficiency of 91% and maximum throughput capacity of 585 kg/hr when the machine was operated at 1,500 rpm for 1.5 hr. In addition, the machine is portable, low energy and easy to operate for any agricultural waste.

Keywords— Size reduction, Waste shredder, Compost, Development, Throughput capacity

1 Introduction

Agricultural residues such as plants, stems and leaves, possess valuable potential for use as animal feed and organic fertilizer. However, farmers often neglect this opportunity due to several reasons. Firstly, many farmers opt to burn food crop waste immediately after harvesting. Additionally, the weight of crop waste poses a challenge for transportation in large quantities to be provided to livestock. The distance from farms to farmhouses or settlements incurs transportation costs, and the lack of a suitable storage medium further complicates the situation. Moreover, farmers are reluctant to store or accumulate waste around their houses due to the fear of fire hazards(Kumar and Kumar, 2015). Furthermore, there is a common assumption among breeders that there is sufficient forage available in yards, gardens, and rice fields to serve as animal feed (El Ghobashy *et al.*, 2023).

Notably, corn waste holds significant potential as a feeding ingredient. Incorporating simple technology, these wastes can be transformed into a nutritious feed and energy source for livestock (Marthiana *et al.*, 2018).

*Corresponding Author

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Recognizing the untapped potential, agricultural waste emerges as a local feed resource to bolster livestock development, particularly in agriculture-based areas (Resmi and Vinod 2022). Efforts to overcome logistical challenges and promote the utilization of agricultural residues can contribute to sustainable farming practices and support livestock development in Nigeria (Ajala *et al.*, 2023). Poor agricultural waste management has led to a decline in agricultural productivity, affecting the fulfillment of food needs (Alabi *et al.*, 2023). Therefore, it is crucial to handle farm residues appropriately, as emphasized by various studies (Kumar and Kumar, 2015; El Ghobashy *et al.* 2023; Marthiana *et al.*, 2018; Resmi and Vinod, 2022). Burning agricultural waste is a common but detrimental practice in waste management, contributing to environmental pollution (Nithya *et al.*, 2023).

Instead of burning, research indicates that absorption of carbon content in the soil was better when the soil was fed with corn stalks than burning of corn stems (Nithya *et al.*, 2023).

Efficient and quick management of large quantities of agricultural waste is essential, especially when faced with limited time and manpower. In this context, the application of appropriate mechanization becomes a necessity to streamline the process of handling agricultural waste effectively. This approach is vital for maintaining agricultural productivity and minimizing the negative impact of improper waste disposal on the environment (Savani *et al.*, 2004). Abdulkadir *et al*. (2020) engineered an agricultural waste shredder, which underwent testing using bean stalks. Their study focused on assessing shredding efficiency and throughput capacity. Employing Response Surface Methodology (RSM), they aimed to optimize machine efficiency across operational speeds of 360, 650, and 975 rpm, paired with sieve apertures of 20, 30, and 40 mm respectively. The highest shredding efficiency, reaching 93%, was achieved with a 20mm aperture and a shredding speed of 975 rpm. Additionally, the machine demonstrated a maximum throughput capacity of 366 kg/h at 975 rpm, while its minimum value stood at 5.14kg/m at 325 rpm. Despite achieving high efficiency, the throughput capacity remained relatively low. In contrast, Resmi and Vinod (2022) introduced a Portable Shredding Machine tailored for rapid composting of organic waste. While their device boasted a capacity of 360 kg/hr, its efficiency was comparatively lower.

The study focused on designed machine to efficiently process all types of agricultural residues through shredding. Its primary goal was to minimize the time spent manually in chopping or thrashing crop residues, providing a cost-effective solution that is accessible to farmers. The development of this machine will not only address the effective utilization of agricultural waste but also prioritizes affordability, making it a valuable resource for farmers seeking efficient and budget-friendly solutions.

2 Materials And Methods

2.1 Design Considerations

Shredder design took into account three factors which include: Mechanical factors considered were strength, rigidity, and the use of simple materials to construct a robust machine. The hopper was designed to handle various sizes of local agricultural waste, and rust-resistant shredding plates were implemented for animal feed hygiene. Operational factors were given significant attention, emphasizing the uniformity of shredded materials, high operational speed for efficient processing, ease of operation and maintenance, and a high level of operational safety. These factors collectively contributed to the machine's effectiveness in processing agricultural waste. Economic factors played a pivotal role in machine development, with a focus on the availability of local materials for fabrication, ensuring low-cost fabrication, and prioritizing cost-effective maintenance strategies. Addressing these economic considerations, designed waste shredder aimed to be accessible and sustainable.

2.2 Design Analysis

2.2.1 Shedder Power Requirement

The power required to shred agricultural waste was considered as one of the important factors for design the operation of the machine, according to Abdulkadir *et al.*(2020) as reported in Equation. (1)

$$P = F \times V \quad (1)$$

Where,

P = power, (Nms^{-1})

F = Shredding force, (N)

V = Velocity (ms^{-1})

While the force required to shredding the waste is given in Equation(2) as reported by Abdulkadir *et al.* (2020)

$$F = m\omega^2 r \quad (2)$$

Where,

F = force required to shred agricultural residues, N

m = mass of shredding blades, g

ω = angular velocity of shaft, rev/m.

$$\omega = \frac{2\pi N}{60}$$

N = speed of shredding (rev/m).

2.2.2 Determination of V – Belt Length

The length of the belt for designed machine was determined using the relationship as reported by Abdulkadir *et al.*(2020) and expressed in Equation(3)

$$L = \frac{\pi}{2}(D_s + D_m)2C + \frac{(D_s+D_m)^2}{4C} \quad (3)$$

Where,

L = Length of the belt, m

C = Center length between the two pulleys, m

D_s = Pitch diameter of the first pulley, m

D_m = Pitch diameter of the second pulley, m

2.2.3 Shedder Diameter

The process of shaft design revolves around accurate determination of the shaft diameter to guarantee optimal strength and rigidity when transmitting power in diverse loading conditions and during machine operations. Typically, the design of ductile material shafts is rooted in considerations of strength, often influenced by the maximum shear theory for a solid shaft experiencing minimal or no axial loading as reported by Abdulkadir *et al*. (2020), Equation (4) expressed the shaft diameter.

$$d^3 = \frac{16}{\pi\tau_{all}}[(K_b M_b)^2 + (K_t M_t)^2]^{\frac{1}{2}} \quad (4)$$

Where,

d = diameter of the shaft, m,

M_t = maximum torsional moment on shaft, Nm,
M_b = maximum bending moment on shaft, Nm
K_t, K_b = fatigue and shock factor for torsion and bending moments (1.5 and 1.0)
S_s = allowable combined shear stress for bending and torsion for steel shaft, (310 N m^{-2}) and π = constant = 3.14.

2.2.4 FACTOR OF SAFETY

The factor of safety ensure the design machine will not fail suddenly which can be obtained using Equation (5) as reported by Abdulkadir *et al*. (2020)

$$FoS = \frac{Y_S}{W_S} \quad (5)$$

2.3 MACHINE DESCRIPTION

The shredding machine consists of key components which include 1.5 Hp petrol engine, a shredding drum equipped with three sets of blades, a feeding tray to receive bio-waste, sieve, engine seat and an outlet. The graphical representation of the shredder 3D view is depicted in Fig. 1, providing an overview of the machine's overall shape. Fig. 2 presents an exploded view, offering a detailed breakdown of its machine structure while Fig.3 illustrates the orthographic view of the designed machine. To facilitate power transmission, the prime mover was connected to the machine through a V-belt. This essential linkage ensures the efficient transfer of power for the machine operation. The combination of these main components and their connectivity through the V-belt system forms the integral structure of the shredding machine, enabling it to effectively process bio-waste.

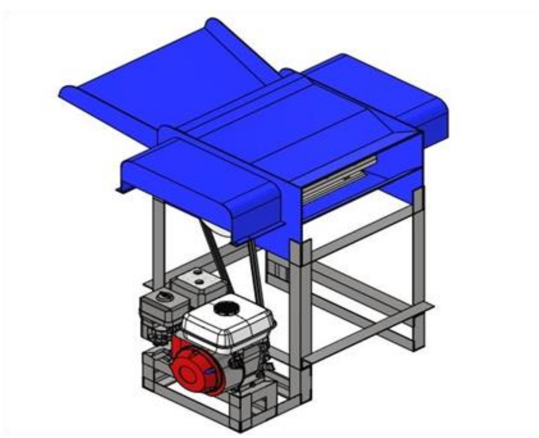

Fig. 1: 3D view of the Designed Shredder

2.4 SHREDDER MODE OF OPERATION

Working principle gives the functionality of the developed model. The developed shredder reduces the human effort as well as human intervention by utilizing the petrol engine for size reduction of agricultural residues The process is very simple as compared to the traditional ways of size reductions. The machine is first connected to the power supply, shredding drum equipped with three sets of blades. After that dry residues/ wastes are fed through the hopper into the cutter assembly. As the post-harvest residues moves towards the cutters, rotating at the varying speeds, the residues get chopped and chopped were collected at the machine outlet.

2.5 PERFORMANCE EVALUATION

The designed and fabricated agricultural waste shredder was tested to evaluate its performance based on Shredding efficiency and throughput capacity using maize straws.

2.5.1 EXPERIMENTAL DESIGN

The experimental matrix was done using Design Expert version 6.0.6, where a Response Surface Methodology (RSM) in a Central Composite Design (CCD) was employed to evaluate the throughput capacity and machine efficiency. The two independent variables, (machine speed and shredding time) and thirteen (13) experimental runs were generated for higher throughput capacity and machine efficiency. The summary of experimental design is shown in Table 1

2.5.2 THROUGHPUT CAPACITY

The throughput capacity of the shredder was evaluated at the five selected speeds of operation namely, 300 rpm to 1,500 rpm. The speed variation was achieved using different pulley arrangement. The throughput capacity was calculated using the relationship in Equation 6

$$TP_C = \frac{W_T}{T} \quad (6)$$

Where,
W_T = total weight of the shredded residues. (kg)
T = time spent for the operation (hr.)

2.5.3 SHREDDING EFFICIENCY

In assessing the shredding efficiency, the initial weight of the waste materials (maize straws) slated for shredding was measured and documented. Likewise, the weights of both the shredded and un-shredded materials were measured and recorded after the operation. All measurements were conducted in kilograms (kg). The shredding efficiency of the machine at five distinct shredding speeds was calculated by employing the relationships specified in Equations (7) and (8).

$$SE = \frac{W_C}{W_T} \times 100\ (\%) \qquad (7)$$

$$W_C = W_T - W_U\ \ (kg) \qquad (8)$$

Where,
SE = Shredding efficiency, (%)
WC = Weight of shredded materials, (kg),
WT = Total weight of the waste (kg), and
Wu = Total weight of un-shredded, (kg)

3 Results And Discussion

3.1 Throughput Capacity

The assessments of the machine's throughput capacity and efficiency are presented in Table 2. The findings revealed a positive correlation between machine speed and throughput capacity. Specifically, at a speed of 1500 rpm, the machine

successfully shredded 585 kg of maize straws with a corresponding shredding time of 1.5 hours. In contrast, at the lowest machine speed of 300 rpm, the total shredded material amounted to 153.6 kg, and the corresponding shredding time was 0.5 hours. These outcomes aligned with the conclusions drawn by Abdulkadir *et al.* (2020) and Ayo *et al*. (2017).

Table 1: The summary of experimental designed

Variable	Parameter	Unit	Level				
			-α	-1	0	+1	+α
A	Machine speed	rpm	300	600	900	1200	1500
B	Shredding time	hr	0.50	1.00	1.50	2.00	2.50

Table 2: Experimental design layout using Response Surface Methodology

Std	Run	A (rpm)	B (hr)	Throughput (kg/hr)	Efficiency (%)
2	1	1500	0.50	195.00	88.00
13	2	900	1.00	366.00	90.00
12	3	900	1.00	365.00	90.50
6	4	1200	1.00	378.00	87.90
7	5	900	0.75	274.50	89.00
11	6	900	1.00	360.00	90.10
3	7	300	1.50	460.80	90.00
1	8	300	0.50	153.60	86.90
4	9	1500	1.50	585.00	89.90
5	10	600	1.00	341.40	87.20
9	11	900	1.00	362.00	89.90
10	12	900	1.00	361.00	91.00
8	13	900	1.25	457.50	91.00

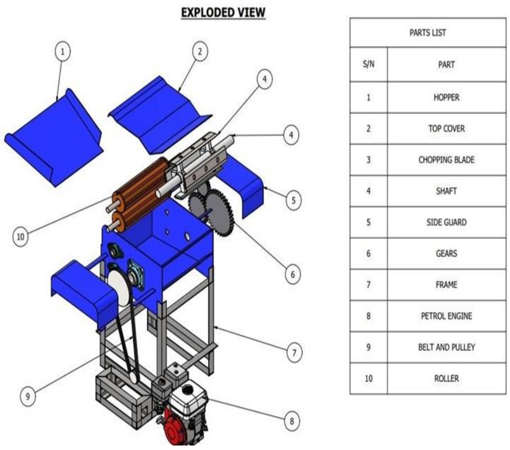

Figure 2: Exploded view of the machine

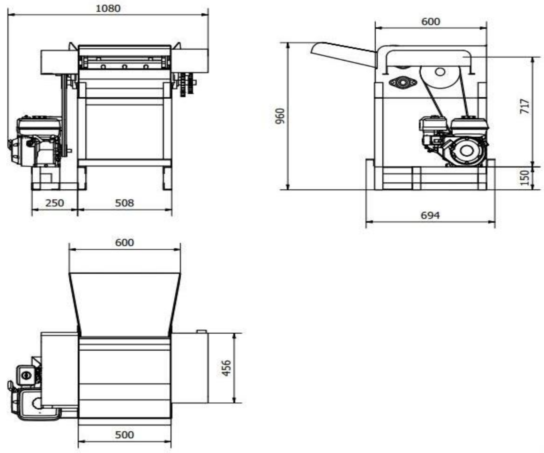

Figure 3: Orthogonal view of the machine

3.1.1 Model Equation for Throughput capacity

The regression model equation formulated for throughput capacity with single factors, quadratic factor, and interactive factors denoted by A, B, B^2 and AB. exhibit a direct proportionality to throughput capacity, signifying a positive impact. Conversely, the coefficient for A^2 has negative impact, as explicitly indicated in the model equation. The model equation obtained for throughput capacity as illustrated in Equation (9).

$$Throughput = 363.58 + 40.78A + 175.27B - 20.02A^2 + 5.18B^2 + 20.70AB \qquad (9)$$

Where,
A = Machine speed, rpm.
B = Shedding time, hr.

3.1.2 Analysis of Shedder Throughput Capacity

Table 3 presents the experimental design details and the outcomes, particularly the throughput of the batch experiments. The fitness of the model is assessed using the coefficient of determination (R^2) and adjusted coefficient of determination (Adj. R^2), with obtained values of 0.999 and 0.998, respectively. These high values affirm the acceptability of the regression model. However, the determination coefficient (R^2 = 0.9656) suggests that 99.00% of the sample variation in the throughput capacity of the designed machine. The

Figure 3: Orthogonal view of the machine

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exceptionally high adjusted coefficient of determination (Adj. R^2 = 0.998) underscores the model's substantial significance, as indicated by Busari *et al*. (2019). According to their findings, a model's fitness is determined by R^2, and the value should not be less than 0.80. Furthermore, the F-value of 2628, coupled with a notably low probability value of 0.0001 (less than 0.05), signifies the significance of the model terms. This supports the conclusion that the model is statistically significant (Busari *et al*., 2019).

3.1.3 Effect of Operating Parameters on the Throughput Capacity

The effect of machine speeds and shredding time were studied on the 3D surface plot (Fig. 4), which depicts the interaction between machine speed and shredding time. It was observed that both operating parameters have significant effect on the throughput capacity of the designed machine.

Table 3: Analysis of variance for throughput capacity of the shredder

Source	Sum of Squares	DF	Mean Square	F - Value	Prob > F	
Model	148053.80	5	29610.76	2628.31	< 0.0001	significant
A	7515.38	1	7515.38	667.08	< 0.0001	
B	138232.8	1	138232.82	12269.80	< 0.0001	
A^2	97.78	1	97.78	8.68	0.0215	
B^2	6.54	1	6.54	0.58	0.4710	
AB	1713.96	1	1713.96	152.13	< 0.0001	
Residual	78.86	7	11.27			
Lack of Fit	52.06	3	17.35	2.59	0.19	
Pure Error	26.8	4	6.70			
Cor Total	148132.70	12				
Std. Dev.	3.36					
Mean	358.45					
C.V.	0.94					
PRESS	1637.11					
R-Squared	0.99					
Adj R-Squared	0.99					
Pred R-Squared	0.98					
Adeq Precision	189.57					

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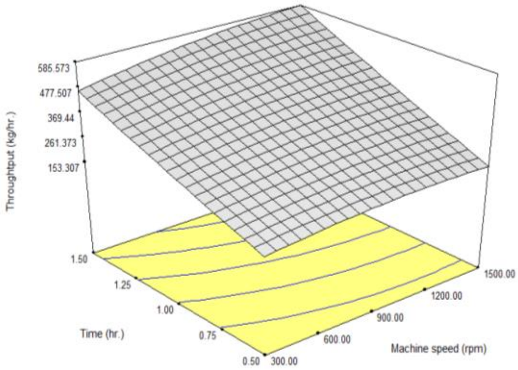

Fig.4: 3D Response surface plot showing the Effect of machine speed and shredding time on the throughput capacity.

3.2 Machine Efficiency

The machine efficiency was evaluated, and the results illustrated in Table 2 and Fig. 5. The results showed that the shredding time have significant effect on the machine efficiency, as shredding time increases efficiency also improved. But the case was slight difference for the machine speed that is increase in machine speeds initially increase the machine efficiency until the machine speed was above 900 rpm and no significant effect was observed and further increase in machine speed resulted in reduction in machine efficiency which contracted to the result obtained by Abdulkadir *et al.*(2020)

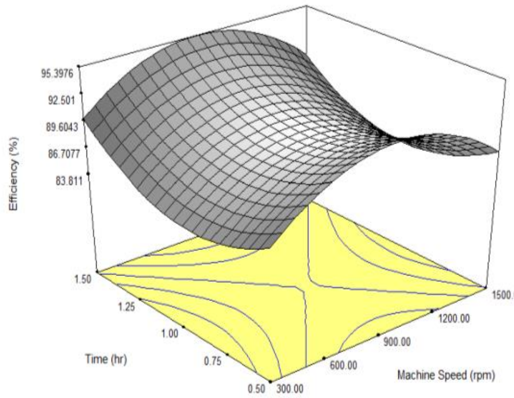

Fig.5: 3D Response surface plot showing the effect machine speed and shredding time on the machine efficiency

4 Conclusion

The key findings from the project work can be summarized as follows:

i. The developed model stands out for its simplicity, efficiency, requires less time, and cost-effectiveness compared to existing models.

Emphasis has been placed on user-friendly operations and, most importantly, on safety. The rotating elements, such as belts and pulleys, are adequately covered, ensuring complete safety for the operator.

i. The maximum throughput capacity achieved at 585 kg/hr. at corresponding 1,500 rpm and 1.5 hr. of machine speed.

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ii. The overall performance of the shredder machine was deemed satisfactory, achieving a 91% when considering the quantity of waste produced relative to the time. However, the potential of harnessing solar energy as an alternative power source opens a realm of opportunities for both small and medium scale farmers to save running costs of operating the machine.

iii.

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